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NEW DIRECTIONS IN RESEARCH ON DYNAMIC DEFORMATION OF MATERIALS

George Mayer

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Progress in the development of new approaches to the analysis and experimental studies of the deformation, failure, and processing of structural materials under high loading rates has been reviewed. Advances in elucidation of the response of materials to high loading rates, with a focus on ceramics, are included. The field of shock synthesis and processing, and directions of future work, have been considered. Special emphasis has been given to materials deformation modes, other prefailure modes, and fracture mechanisms, since these are the concepts that are key to hydrocode development and accurate modeling of real material behavior under high loading-rate conditions.

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PREFACE

This paper was prepared in response to Novel Concepts for Tactical Technology, DARPA Project Assignment A-140, Amendment No. 2, 7 March 1991. IDA was tasked to monitor and evaluate advances in the analytical and experimental approaches to deformation, failure, and processing of armor and warhead materials, including a determination of needs in research. This paper assesses the relevant activity and progress in the field and defines areas where additional research is needed.

The author would like to thank Professor Marc Meyers of the University of California at San Diego, Dr. Janet Sater and Mr. Peter Kysar of IDA, and LtCol Patrick Sullivan, USMC (Ret.), formerly of DARPA, for useful suggestions.

ABSTRACT

Progress in the development of new approaches to the analysis and experimental studies of the deformation, failure, and processing of structural materials under high loading rates has been reviewed. Advances in elucidation of the response of materials to high loading rates, with a focus on ceramics, are included. The field of shock synthesis and processing, and directions of future work, have been considered. Special emphasis has been given to materials deformation modes, other prefailure modes, and fracture mechanisms, since these are the concepts that are key to hydrocode development and accurate modeling of real material behavior under high loading-rate conditions.

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EXECUTIVE SUMMARY

The advent of advanced, powerful, complex weapons and warheads in modern guns and missiles has created major protection problems for the armor community. The areas cited most often as difficulties have been:

1. Large expenses and long times involved in small- and full-scale testing of armor configurations.
2. Processing and manufacturing of effective advanced armor systems (especially those involving ceramic materials) at reasonably low cost, and with reproducible results.
3. Lack of comparability of test results between investigators, due to differences in testing methods, lack of control over or knowledge about material preparation, condition, chemistry, and microstructure.

This paper addresses the first two topics above, and the routes to circumventing the problems cited. The third topic is to be addressed in a forthcoming IDA paper.

Central to the issue of avoiding large costs in full-scale armor testing is the development of understanding of mechanisms of energy absorption and dissipation for a range of advanced engineering materials under complex high loading-rate conditions. Related to this area are the development of real-time, in-situ diagnostics, the definition of key variables controlling dynamic mechanical behavior of the materials studied, and the collection of a reliable data base of dynamic mechanical properties of materials over a range of key variables, such as temperature and strain rate. This understanding of the micromechanisms and modes of deformation and failure under high loading rates is a prerequisite to the development of more accurate computer models and attendant hydrocodes. Recent developments in supercomputing and parallel processing, together with the foregoing, point to pathways for avoidance of much expensive instrumented armor range testing.

With regard to ceramic materials, dynamic loading has been put to good use as an aid in compaction of ballistic tiles, in association with a novel intense heating and consolidation process called self-sustaining high-temperature synthesis or SHS.

Finally, promising areas have been defined for research and development in shock-processing, hydrocodes, and materials energy absorption and dissipation, and deformation and failure under high loading rates.

I. INTRODUCTION

Studies of the dynamic loading and corresponding response of materials have multiplied during the past 10 years, as exemplified by the host of papers presented at conferences and symposia that have been held on a regular basis (see, for example, Refs. 1-10). Because the area of dynamic loading is so broad, many topics, such as the treatment of detonations, shock phenomena relating to the earth, and hypervelocity studies, are not mentioned here or are mentioned merely in passing. Suffice to say that significant attention is being devoted to these other important areas, and that they have been addressed regularly at the meetings already mentioned.

The two main areas of application that are of interest to the Defense Advanced Research Projects Agency (DARPA) and the Department of Defense (DoD) are reflected in the research activities, progress, and future directions of the field; they are armaments (armor, warheads, etc.) and shock synthesis and processing of materials. Granting this bias, more general extensions of the activities described will be seen by the reader.

In the decades of the Cold War, the DoD became increasingly concerned about both the numbers and effectiveness of the conventional weaponry of the Soviet Union and their allies in the Warsaw Pact nations. The approach that was taken was to meet numbers of tanks and guns with smaller numbers of highly effective new weapons. On the research front of high loading-rate phenomena, before embarking on new materials and other development programs, the state of understanding and areas of ignorance had to be established. The applications for new armaments were important, as is indicated in Figure 1. Thus, in 1977, the DoD asked the National Materials Advisory Board to study the problem of the state of the art and research needs in the area of high loading-rate phenomena. A committee (the so-called Herrmann Committee) was established for this purpose. Their report "Materials Response to Ultra-High Loading Rates" (Ref. 11) is still widely referenced, and the study was used as a guide by many DoD agencies for the support of research during the past decade.

With regard to shock synthesis and processing, the interests on the part of research sponsors stemmed from the possibilities of creating new materials thereto unknown,

strengthening and hardening of materials by novel means, development of new joining methods, and less expensive routes to fabrication of advanced materials, such as intermetallics and ceramics. While shock processing of materials had been somewhat successful in the late 1950's and 1960's, the methods have not been widely used in the United States. An excellent review of previous industrial applications of shock waves is provided in Reference 8. In the Soviet Union, shock processing has been much more intensively studied and, it is believed, has been utilized for both commercial and military applications (Ref. 12).

Areas of Application
• Armor protection
• Penetration phenomena
• Shock wave effects on structures
• Fragmentation
• Spallation
• Shaped charge jet formation

Figure 1. Applications Areas in Armaments for Dynamic Loading Phenomena

II. REVIEW OF PROGRESS AND PROSPECTS

The broad impact of the Herrmann report and its recommendations can be realized from the progress that has been made in the 10 years since the publication of the report. For example, one of the major issues at the time was the separation of the numerical modelling community from the sector dealing with dynamic material property measurements, and the segment involved with test firings. Much broader cooperation exists now, as seen by the development of more physically realistic constitutive models which interface well with complex hydrocodes. Some examples are discussed later in this paper. Such cooperative development has extended successfully into ceramic armor materials, with the Ceramics Modelling Working Group, organized in 1988 by G.E. Cort of the Los Alamos National Laboratory and composed of representatives of all three communities.

In 1980, a high priority for research was the elucidation of mechanisms of dynamic failure by brittle crack propagation, ductile void growth, and adiabatic shear banding, and the subsequent incorporation of these failure modes, through models, into hydrocodes. As an example of progress, there has been intense research, both theoretical and experimental, into shear banding. Four widely different studies are described in References 13-16. For example, a model of shear banding was developed employing the concept of the energy dissipated by a moving dislocation (Ref. 13). From direct observations of shear localization with high-speed photography, the energy dissipated in a band and the resulting temperature rise were estimated (Ref. 14). Over the years, better resolution and sensitivity have been brought to the measurement of shear band temperatures, the most recent being done with an elaborate array of infrared detectors (Ref. 17). The method of caustics was applied to problems of high-speed crack propagation by Kalthoff (18) and Rosakis (19). Briefly, this method employs light rays of a parallel-light beam to illuminate a specimen. When a crack propagates through the area illuminated, the light rays experience slight deviations from their original directions. The deviations result in nonuniform light distributions in so-called shadow planes, located behind or ahead of the specimen. In turn, the light distributions represent quantitative descriptions of the stress concentrations in the specimen. This method of examination, sometimes termed the shadow optical method of

caustics, is being extended to localizations of strain such as shear bands, and promises to provide important fundamental information. On the side of theoretical approaches, perturbation analyses have been developed by Molinari and Clifton (20) and Wright and Walter (21) to address shear localization and adiabatic shear banding.

The development of new dynamic mechanical property tests for materials under well-characterized and controllable loading conditions was also listed as a need in 1980. Many novel testing methods and equipment have been developed since that time, including a pressure-shear plate impact test (Ref. 22) for shear strain rates up to $10^5 s^{-1}$ and controllable levels of nearly hydrostatic pressure, a high-speed torsional testing machine (Ref. 23), and a Taylor anvil impact test performed with an instrumented compression Hopkinson bar (Ref. 24). On the subject of detection methods for following cracks, a white light speckle method with high-speed photography (Ref. 25) and moiré photography (Ref. 26) have been employed to assess the dynamic displacement fields and dynamic stress intensity factors of fast cracks. A major new diagnostic tool for probing the internal events during projectile/target impact in thick sections of steels, ceramics, etc., has been successfully developed and applied at the Los Alamos National Laboratory (Ref. 27). The system, called PHERMEX, is an acronym for pulsed high energy (30 MeV) radiographic machine emitting x-rays. This development should assist in the elucidation of failure modes in full-scale, advanced armor materials.

Studies of the characterization of dynamic brittle fracture in both metals and ceramics based upon a description of the nucleation, growth, intersection, and coalescence of cracks have only begun, e.g., Reference 28. Among the many approaches taken toward dynamic fragmentation of brittle materials is the development of a model based on particle size statistics combined with molecular-dynamic simulations by Grady (29). Existing models, such as the SRI NAG/FRAG flaw nucleation and growth models, developed for metallic materials, should be explored in ceramics and possibly extended to include crack intersections and coalescence to failure. A new ceramics model may have to await a more complete characterization of failure modes over a range of strain rates.

A related subject which required attention within the arena of dynamic loading of materials was the development of more detailed descriptions of materials behavior at ultrahigh rates of loading. The controlling micromechanisms of deformation and failure, and ranges where they dominate, should be identified. For this problem, it would seem ideal to develop a form of failure mechanism diagram, after Ashby's scheme (Ref. 31).

Figure 2 shows two examples developed for an alumina ceramic deformed in (a) tension and (b) compression. The differences in the maps illustrate (over a range of fairly slow-strain rate) where certain failure mechanisms dominate and the regions where they prevail. The information can be used in two ways. First, by specifying the stress, temperature, strain-rate, and load state (in these two cases, tension or compression), the map will provide information of use for developing constitutive models. In addition, to avoid a particular failure mode, there may be flexibility in changing the grain size or other microstructural feature, altering the load or temperature, or limiting the strain-rate that the material experiences. With changes in grain size or other key material variables, the regimes within the failure mechanism diagram could change significantly.

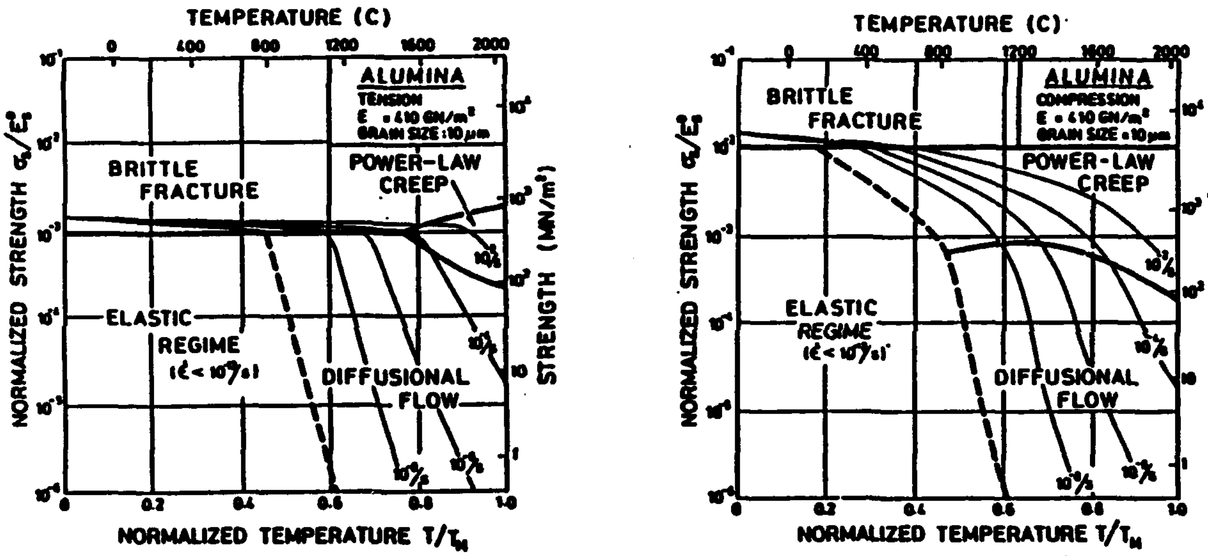

Figure 2. Failure-Mechanism Diagrams for a Ceramic (Alumina) Loaded in (a) Tension, and (b) Compression (from *Cellular Solids-Structure and Properties*, 1988, by L.J. Gibson and M.F. Ashby, Courtesy of Pergamon Press)

The foregoing are examples of topics within the broad field that have received concerted attention in the past decade in dynamic loading of materials. In order to systematically sort out our understanding in more comprehensive fashion, Figure 3 lists some important research areas which should receive continuing and new emphasis. Much progress has already been made on sorting out the roles of microstructure and defects and some of those results have been reported (Refs. 32, 33).

Research Areas for Added Emphasis
• Development of data bases of dynamic properties of materials under well-described, reproducible conditions
• Continuing studies of the roles of microstructure and defects in dynamic deformation and fracture
• Construction of Ashby deformation and fracture maps over a wide range of loading rate and temperature regimes
• Detailed studies of yield, deformation, and failure as a function of loading rate for advanced materials
• Expanded diagnostic spectrum of in-situ detection, with increased speed, resolution, and sensitivity of measurement
• Continuing studies of the roles of microstructure and defects in dynamic deformation and fracture

Figure 3. Research Areas for Continuing and New Emphasis in Dynamic Loading

There has been recent interest in the behavior of ceramic materials under dynamic loading, e.g., on the role of pre-existing crack networks, their growth and coalescence, and the behavior of pulverized and rubberized ceramic and glassy materials under projectile impact. Figure 4 indicates topics that need additional attention.

Dynamic Loading Issues in Ceramics
• Kinetics of crack nucleation, growth, and intersection
• Mechanisms of cracking under high dynamic compressive stresses
• Development of damage models
• Constitutive modelling of pulverized, confined ceramics
• Energy dissipation phenomena
• Effects of phase transformations on energy dissipation
• Process zones in ceramics
• Methods for measuring dynamic fracture toughness

Figure 4. Research Issues in Dynamic Loading of Ceramic Materials

Two subjects of major activity in dynamic loading deserve special mention. These are modelling and code development, and synthesis and processing of materials. The following sections address these topics.

A. MATERIALS MODELS AND CODE DEVELOPMENTS

Wider use of hydrocodes by the shock wave community to simulate materials response to high loading-rate events has occurred over the past two decades. This was due to the complexity of dynamic events, levels of pressure and temperature achieved, the novel new materials employed in the systems being used, and, finally, because of the high and still escalating costs of full-scale testing in areas such as ordnance. The numerical simulations which undergird these codes have been facilitated by new supercomputers and by advanced methods, such as parallel processing. An excellent review of hydrocode concepts has been given by Anderson (Ref. 34) and earlier by Zukas and colleagues (Refs. 35, 36). The proliferation of codes has been a mixed blessing. On the one hand, some problems of increasing complexity under extreme conditions are being successfully addressed by individual codes; on the other hand, little compatibility exists between codes, and it is very costly and often restrictive (e.g., created by the need for supercomputers, or restricted by classification) to maintain all of the codes in use today. Data collection has been fairly expensive and the accuracy of codes to describe a broad range of problems has been limited.

Examples of some of the codes that have been popular and used widely and successfully to address real armament problems are listed in Figure 5. The pros and cons of Lagrangian and Eulerian codes have been examined at length. For example, Lagrangian codes are generally more computationally efficient, need a smaller number of zones than Eulerian codes for equivalent accuracy, and avoid mixed material cell computations. The Lagrangian calculations allow the behavior at material interfaces (e.g., opening of voids) to be computed employing the concept of slidelines (Ref. 37). The Lagrangian approach also allows superior treatment of material behavior (constitutive relations, strain hardening, etc.). On the negative side, large grid distortions create great problems for these codes, and users have often shifted to Eulerian codes for large deformation problems where there is extensive local flow, in high velocity impact regimes, for the collapse of shaped charges, in turbulent flows, etc. In recent years, codes have been adapted to account for intense localized failure modes, such as adiabatic shear and erosion (Ref. 38). With the aid of such new capabilities, some Lagrangian codes (e.g., EPIC) can extend to treat "selected" large

deformation problems. A general problem (though more prevalent with Eulerian codes) is the need for large computer memories and long processing times, thereby increasing the expenses of calculation.

Examples of Hydrocodes	
Lagrangian (Finite Element)	Eulerian (Finite Difference)
HEMP	HULL
DYNA	JOY
PRONTO	CTH
EPIC	MESA

Figure 5. Some Examples of Hydrocodes Used in Numerical Simulations

Much progress has been made in developing better constitutive models for use in hydrocodes. The Johnson-Cook model (Ref. 39) has been widely accepted for several years, and updates for use in EPIC are periodically made. Other models which take into account specific materials parameters, such as microstructure and dislocation behavior, are the Zerilli-Armstrong model (Ref. 40) and the Mechanical Threshold Stress or MTS model of Follansbee (Ref. 41). Sandia National Laboratories have developed a mesocrack continuum damage model for brittle materials (Ref. 42), based on the notion that many brittle materials contain pre-existing microcrack networks. The initiation, growth, and interaction of such cracks contribute to the nonlinear response of these materials and the latter are not predictable by classical fracture mechanics theories. This model has been useful in predicting the dynamic response of quasi-brittle materials under tensile loads.

More recently, significant advances have been made in developing a new generation of codes which combine the favorable aspects of Lagrangian calculations with limited Eulerian features for avoidance of mesh distortion (Ref. 43). The techniques are Arbitrary Lagrangian Eulerian (ALE) and Free Lagrange. The ALE method has recently been extended to allow multimaterial zones, as well as nonoscillatory second-order-accurate advection routines, which are necessary for accurate computations. The key to making the ALE technique efficient was the development of automatic criteria (as measured by grid distortion) to switch a cell from Lagrangian to Eulerian.

Reducing the number of working hydrocodes seems to be a truly formidable task, in view of the range of problems addressed by these codes, from determining the response of structures to blast waves, to penetration, and to retorting of oil shale, etc. The trends to combine the best elements of different codes, such as ALE, and attempts to combine two- and three-dimensional codes into one that treats both dimensions, e.g., a new EPIC code (Ref. 44), are promising directions. Figure 6 lists some continuing needs in the hydrocode arena. Although the list appears formidable, progress is being made on a number of fronts. For example, the advent of larger and faster computers has allowed three-dimensional versions of some hydrocodes to be formulated (Ref. 45). Also, among new ventures to provide base-line data for hydrocodes, what appears to be a comprehensive effort is on-going at Sandia (Ref. 46). By and large, however, inadequate comparability exists between data bases for advanced materials for a variety of reasons. In many cases, the materials undergoing dynamic tests have not been well characterized. In other instances, test conditions have not been reproducible or adequately controlled.

Hydrocode Advances--Selected Needs
• Extend ALE to Three Dimensions
• Generalize Adaptive Mesh Refinement
• Narrow the Gap Between Practical Hydrocodes and Physically Based Models
• Anisotropic Materials Response
• Fracture Initiation Criteria (Ductile and Brittle Materials)
• Mechanism(s) and Models of Softening from Damage Accumulation (Ductile and Brittle Materials)
• Mechanisms and Models of Fracture Propagation (Ductile and Brittle Materials)
• Comprehensive Materials Property Data

Figure 6. Some Future Needs for the Advancement of Hydrocodes

B. SHOCK SYNTHESIS AND PROCESSING OF MATERIALS

The area of shock processing of materials (used in the broadest sense) has seen concerted interest during the past three decades from the 1963 book on *Explosive Working*

of Metals by Rinehart and Pearson (Ref. 47) to the fairly recent volume on *Shock Waves for Industrial Applications*, which was brought together by Murr in 1988 (Ref. 8).

The early efforts in processing (Fig. 7) employing shock waves were focused on explosive forming, often of large shapes such as hemispherical sections or cones, on surface hardening, and on explosive welding (Ref. 48) and bonding or cladding. Interests in shock synthesis of diamond were spurred by the work of DeCarli and Jamieson (Ref. 49) in 1961. DeCarli's patent (Ref. 50) was followed by more patents and industrial applications of shock-synthesized diamond by the DuPont Company (Ref. 51). Somewhat after his success with diamond, DeCarli demonstrated the successful shock synthesis of cubic BN from the hexagonal phase (Ref. 52). Successful shock syntheses of hard materials and other materials of technological interest (e.g., intermetallics) have proceeded strongly in the Soviet Union, Japan, and the United States during the past three decades. These have been reported at previous meetings (Refs. 4, 9) and were presented recently (Ref. 53).

Early Areas of Activity
• Explosive Forming • Explosive Welding • Explosive Hardening • Explosive Cladding

Figure 7. Early Areas of Activity in Shock Processing of Metals

Dynamic processing and synthesis of materials have been of strong interest in the United States, especially during the past decade, and this has been reflected in two studies by the National Materials Advisory Board (Refs. 54, 55). Shock consolidation has been of interest for the densification of materials which are normally difficult to sinter, to avoid grain growth, and to seek a cost-effective industrial production method. More recently, dynamic consolidation has been combined with combustion synthesis (or self-sustaining, high-temperature synthesis) to yield ceramic and ceramic composite compacts close to full density (Refs. 56, 57). Figure 8 shows a titanium carbide disk which was recently

dynamically compacted along with the combustion synthesis step to high density. Figure 9 lists the more recent areas of activity in shock synthesis and processing.

Temperature predictions for shock processing have been made using hydrocodes and thermal analysis models (Ref. 58). Although careful and systematic approaches have been taken to explain the generation of dislocations and other defects during shock loading (Refs. 59, 60), questions of defect nucleation mechanisms remain. These questions were recently addressed (Refs. 61, 62). Figure 10 lists a series of areas that deserve future study. For example, transient and/or intermediate states that are generated during shock loading need to be treated both theoretically and experimentally. On a related topic, in an earlier work (Ref. 63), diffusion coefficients under shock loading were reported to be 10^2 to 10^3 higher than normal, but no theoretical model was offered. The problem of mass transport over relatively large distances in short times has been difficult to explain. In a different vein, electrical phenomena have been reported in association with shock-related processing and fracture (Ref. 64). It has also been reported that shock activation of catalyst materials can increase the reactivity of the catalysts by three orders of magnitude (Ref. 55). This may represent an important practical effect, if it can be retained for a reasonable period of time.

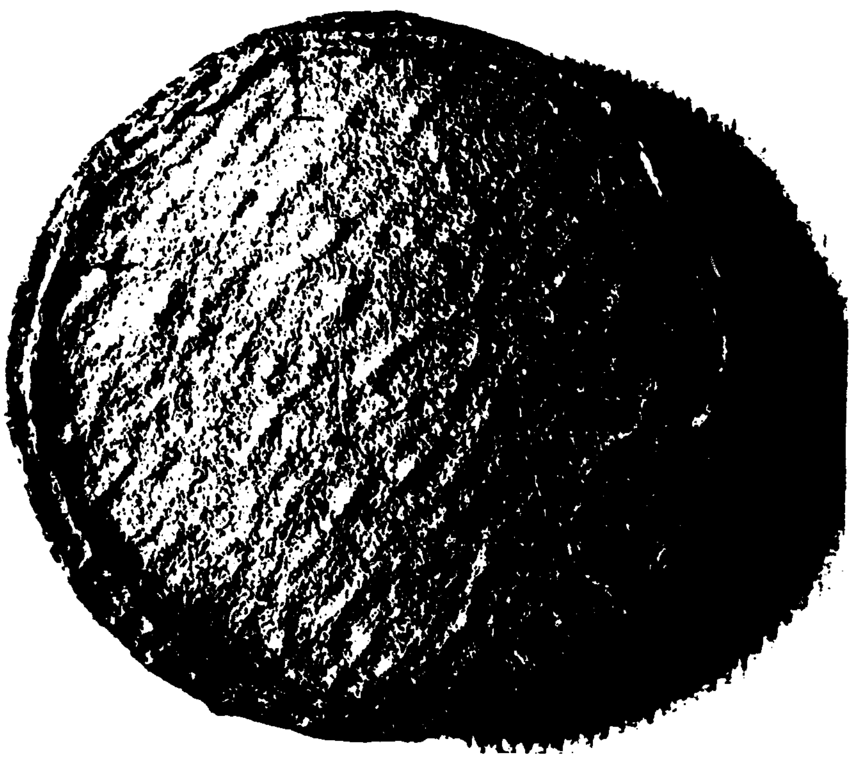

Figure 8. Specimen of 4-Inch-Diameter Disk of Titanium Carbide Fabricated by Combustion Synthesis and Dynamic Compaction (cracks are surficial) (Courtesy of M.A. Meyers, University of California at San Diego)

Recent Areas of Activity
• Powder Compaction
• Phase Transformations
• New Compound Synthesis
• Combustion Synthesis (SHS)
• Chemical Decomposition
• Polymerization and Cross-Linking
• Shock Modification and Activation

Figure 9. Recent Activities in Shock Synthesis and Processing of Materials

Areas for Future Study
• Nucleation of Defects
• Roles of Defects as Precursors
• Void Collapse in Porous Materials
• Transient or Intermediate States
• Diffusion Phenomena
• Electrical Phenomena Associated with Fracture
• Nonequilibrium Temperatures in Shock Front
• Measurement of Temperature and Shear Stress in Dynamics Compression
• Continued Emphasis on Tailoring of Shock Profiles and Containment Designs for Fracture Avoidance

Figure 10. Subjects in Shock Synthesis and Processing That Require New Emphasis

III. FUTURE DIRECTIONS

The areas of on-going activity in high loading-rate effects on materials and the need for increased understanding detailed in the foregoing represent a base of opportunity for a rapidly widening field of research. In the future, more complex materials such as composites (metallic, ceramic, and organic), laminates, intermetallics, and hybrids will constitute special challenges for the high loading-rate community.

Hypervelocity impact will receive increased attention because of new weapons developments. Systems such as electromagnetic launchers (Ref. 65) and multistage gas dynamic launchers (Ref. 66) bring novel experimental capabilities to this arena. Studies that have broad applications from armament, to geosciences, to space can be based upon such new experimental capabilities.

Finally, new computing capabilities on the horizon will enable computations to be made that are impossible or impractical with machines that are available today (Ref. 67) (Fig. 11). New parallel processing machines and capabilities will also facilitate access to large-scale, complex problems by a wider community of researchers.

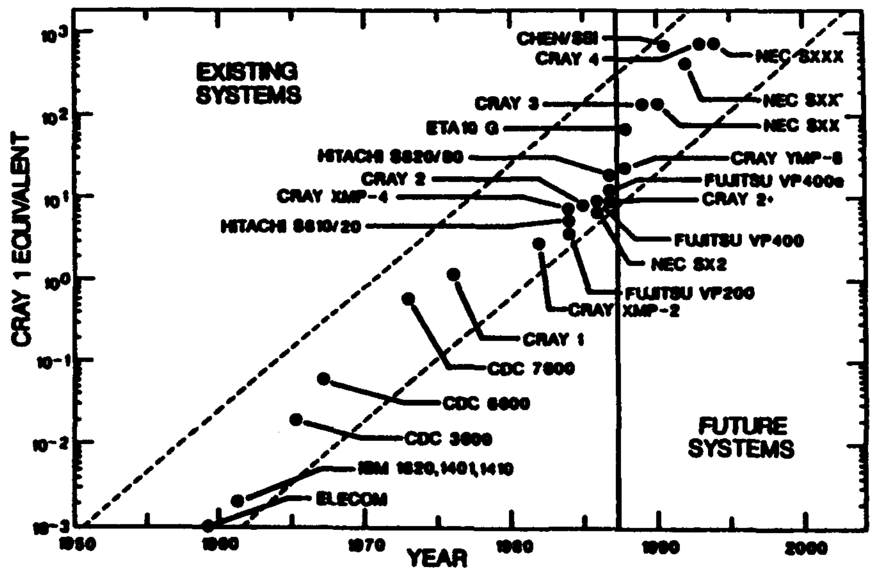

Figure 11. Trends in Supercomputing Capabilities (Courtesy of National Materials Advisory Board)

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